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Title Page

Title: Mapping Cortical Surface Features in Treatment Resistant Schizophrenia with in vivo structural MRI

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Abstract

Decreases in cortical volume (CV), thickness (CT) and surface area (SA) have been reported in individuals with schizophrenia by in vivo MRI studies. However, there are few studies that examine these cortical measures as potential biomarkers of treatment resistance (TR) and treatment response (NTR) in schizophrenia. This study used structural MRI to examine differences in CV, CT, and SA in 42 adults with schizophrenia (TR=21, NTR=21) and 23 healthy controls (HC) to test the hypothesis that individuals with TR schizophrenia have significantly greater reductions in these cortical measures compared to individuals with NTR schizophrenia. We found that individuals with TR schizophrenia showed significant reductions in CV and CT compared to individuals with NTR schizophrenia in right frontal and precentral regions, right parietal and occipital cortex, left temporal cortex and bilateral cingulate cortex. In line with previous literature, the temporal lobe and cingulate gyrus in both patient groups showed significant reductions of all three measures when compared to healthy controls. Taken together these results suggest that regional changes in CV and CT may index mechanisms specific to TR schizophrenia and potentially identify patients with TR schizophrenia for earlier treatment.

KEY WORDS: Schizophrenia, Treatment Resistant, Cortical Thickness, MRI, Cortical Volume

1. Introduction

Schizophrenia is a psychiatric disorder characterized by symptoms such as hallucinations, paranoia, and delusions. As such, schizophrenia is often associated with life-long disability, increased risk of mortality, significant social and economic cost due to long-term unemployment (Velligan et al., 2009). Delays in seeking and identifying effective treatment following the onset of schizophrenia is correlated with illness duration, loss of social and occupational function, and increase in treatment resistance (Elkis and Buckley, 2016; Harvey and Rosenthal, 2016). Contemporary first-line antipsychotic medications such as olanzapine, risperidone and haloperidol have shown significant efficacy in treating schizophrenia, predominantly through the blockade of dopaminergic (D₂) receptors (Bodén et al., 2017; Goghari et al., 2010; Jørgensen et al., 2016). Despite the widespread use of dopaminergic agents, approximately one third of patients with schizophrenia demonstrate resistance to traditional anti-psychotic treatments, suggesting an alternative mechanism of action may underlie symptoms in these individuals (Elkis and Buckley, 2016; Harvey and Rosenthal, 2016; Nakajima et al., 2015). Clozapine remains the most viable treatment for such patients. However, clozapine is associated with severe side effects resulting in poor patient tolerance and adherence (Chakos et al., 2001).

Theories proposed to explain resistance to first line anti-psychotics include the continuum perspective, suggesting that treatment resistant schizophrenia (TR) is a more severe form of schizophrenia, and the heterogeneity theory, suggesting TR is a separate and categorically different form of illness underpinned by a different neuropathological mechanism. Current evidence suggests that delays in seeking treatment is correlated with poor outcome, which may support a third neurodegenerative theory suggesting that TR can be induced and worsened by increased environmental insults and lack of effective treatment (Howes and Kapur, 2014;

Szeszko et al., 2012; van Haren et al., 2008). However, a likely explanation of TR in patients with schizophrenia may include more than one of these aforementioned theories, which may overlap and predispose patients to a TR trajectory.

Understanding how these theoretical approaches to schizophrenia relate to the neurobiological mechanisms underlying TR is important to the development of novel treatment approaches to TR patients and improving diagnostic approaches to first episode psychosis. Differences in brain structure and function in TR patients relative to those who respond to first line dopaminergic agents (NTR) indicates the possibility of these measures being developed into imaging biomarkers to identify patients at risk of resistance to first-line treatment, and those suitable for earlier clozapine treatment. Investigation into neurobiological changes which are associated with aspects of schizophrenia that are specific to TR may be used reliably to identify TR and potentially clinically reduce risk associated with delays in efficient treatment.

Neuroimaging studies using high resolution MRI (Magnetic Resonance Imaging) demonstrate widespread differences in patients with schizophrenia in cortical grey matter volume (CV) (Anderson et al., 2015; Molina et al., 2010, 2008, 2005; Mouchlianitis et al., 2016; Zugman et al., 2013) cortical thickness (CT) (Heinrichs et al., 2017; Kuperberg et al., 2003; Narr et al., 2005; Nesvåg et al., 2008; Plitman et al., 2016; Rimol et al., 2010; Smiley et al., 2012; Sugihara et al., 2017) and surface area (SA) (Kong et al., 2015; van Haren et al., 2012; Xiao et al., 2015) compared to healthy controls (HC) (Maller et al., 2012; Quarantelli et al., 2014; Selemon and Goldman-Rakic, 1999). CV reductions in patients with schizophrenia are one of the most common findings in the condition, beginning with global grey matter reductions and associated increases in ventricular volume (Emami et al., 2016; Harvey et al., 1993; Honea et al., 2005; Kong et al., 2015; Shergill et al., 2001). Further studies have highlighted the importance of investigating CT and SA in addition to CV alone as each of these component measures has been shown to represent unique aspects of cortical architecture (Rakic, 1995) with different

aetiologies, genetic determinants (Nesvåg et al., 2008; Panizzon et al., 2009) and neurodevelopmental trajectories (Ecker et al., 2014). CT has been shown to be influenced by a number of neuro-developmental factors including neuronal size, intra-neuronal neuropil, number of glial cells and blood vessels (Rakic, 1995). SA expansion has been attributed to the proliferation of cortical neuronal columns (Crespo-Facorro et al., 2000; Rakic, 1995). Thus, determining which of these measures procures CV differences in TR could contribute to understanding the underlying pathogenesis of TR and the effects that antipsychotics have on cortical morphology. However, in previous research few studies explored the relationship between cortical measures and treatment response directly.

Longitudinal assessment of CT and SA has demonstrated significant degeneration of frontal, temporal and parietal grey matter over time in patients with schizophrenia (van Haren et al., 2012). Furthermore, significant decreases in CT in the temporal lobe and in CV and CT of the dorso-lateral prefrontal cortex (dlPFC) have been noted in TR compared to NTR schizophrenia (Zugman et al., 2013). In addition, CT in the temporal lobe has been associated with treatment response and remission (Szeszko et al., 2012). Based on these reports, a link between temporal lobe CT and persistence of symptoms such as auditory hallucination or the failure of the mechanism identifying such hallucinations as internally generated has been proposed (Emami et al., 2016; Rimol et al., 2010; Shergill et al., 2001). Taken together, these results indicate that cortical surface measures in both the frontal and the temporal lobe may be an indicator of treatment resistance in schizophrenia patients. Therefore, this study aims to explore the differences in these cortical measures between TR and NTR patients and HC to establish whether there are specific cortical indicators of schizophrenia and different cortical indicators of TR.

In order to limit confounding variables in our patient groups, crucially, we controlled for potential influences on cortical measures such as age, medication dosage, illness onset and

duration, and we recruited only patients who are not treated with clozapine. These exclusion criteria allowed us to maintain the homogeneity of the populations sample while continuing to meet the criteria for TR. To our knowledge this is the first study of cortical morphology to stratify a sample in this way. We test the hypotheses that *i*) we will see a decrease in CV, CT and SA in all patients compared to HC, *ii*) TR patients will exhibit CV, CT and SA reductions in the frontal and temporal lobes compared to NTR and *iii*) the extent of these cortical changes will positively correlate with symptom scores in the TR group. By identifying differences in cortical structure between TR and NTR patient groups we aim to identify neuroanatomical features to further the understanding, identification and stratification of TR schizophrenia.

2. Methods

2.1 Subjects

We recruited 42 patients who satisfied ICD-10 1992 criteria for schizophrenia from the South London and Maudsley (SLaM) National Health Service (NHS) and 23 HC within the same range of age, sex, and socioeconomic status. The patient population was stratified into TR ($n=21$) and NTR ($n=21$) groups. The criteria for inclusion in the TR group included: at least two prior drug trials of 4-6 weeks duration with no clinical improvement and persistent psychotic symptoms as defined as a score of at least 4 (moderate) on at least two positive symptom items of the Positive and Negative Syndrome Scale, PANSS (Kay et al., 1989), with a duration of over 5 years. Patients in the NTR group were defined by a score of 3 or less (stable for at least 6 months) on all items of the PANSS (Andreasen et al., 2005; Conley and Kelly, 2001). No patients had been on clozapine in the last 6 months. IQ was measured with the two-item Wechsler Abbreviated Scale of Intelligence, WASI (Wechsler, 2008). Chlorpromazine (CPZ) equivalent doses of medications were calculated using conversion tables (Bazire, 2016; Woods, 2003). Further demographics and clinical data are presented in Table 1.

2.2 Procedure

2.2.1. Magnetic Resonance Imaging

MRI was performed using a General Electric MR750 3T scanner. A T1-weighted spoiled gradient three-dimensional magnetization prepared rapid acquisition was used to acquire high-resolution structural images of the brain (repetition time, 7.312ms; echo time, 3.016ms; flip angle 11°; matrix size 256x256; field of view, 270) with 196 sagittal positions (at 1.2 x 1.05 x 1.05mm resolution).

2.2.2. Cortical Reconstruction with FreeSurfer

Cortical surface reconstruction of each subject's T1-weighted volumetric images was performed using FreeSurfer 5.2.0 (*freesurfer.net*). This resulted in a white matter and outer pial (i.e. grey matter) surface mesh for each subject (Dale et al., 1999; Fischl et al., 1999; Fischl and Dale, 2000; Jovicich et al., 2006; Ségonne et al., 2004). All surfaces were visually inspected for errors in reconstruction in comparison to the underlying T1-weighted image in line with standardised QA protocols (Dale et al., 1999; Jovicich et al., 2006; Ségonne et al., 2004). Subjects with poor quality reconstructions were subsequently removed and are not described in this study (TR=1, NTR=1). In addition to vertex-wise measures of CV, CT was estimated as the distance between corresponding vertices on the white matter and outer grey matter (i.e. pial) surface (Dale et al., 1999). Vertex-wise estimates of SA were also derived on the grey matter surface using a pycnophylactic or mass preserving interpolation method (Dale et al., 1999). Prior to any further statistical analysis each measure was smoothed using a 10mm FWHM surface based Gaussian kernel.

2.2.3. Statistical Analysis of Cortical Measures

To assess the relationship between vertex-wise measures of CV, CT, SA, and clinical measures of interest, we used a general linear model (GLM) based multiple regression approach with diagnostic group and sex as fixed-effect factors and age, IQ, total PANSS score, and medication dose as continuous co-variates:

$$Y_i = \beta_0 + \beta_1 \text{Group} + \beta_2 \text{Sex} + \beta_3 \text{Age} + \beta_4 \text{IQ} + \beta_5 \text{PANSS} + \beta_6 \text{Meds} + \varepsilon_i,$$

where ε_i is the residual error at vertex i . Between group differences were estimated from the corresponding coefficient β_1 , normalised by the corresponding standard error. Corrections for

multiple comparisons across the whole brain were performed using random field theory (RFT) based cluster analysis using a cluster-based significance threshold of $p < 0.05$ (2-tailed (Hayasaka et al., 2004; Winkler et al., 2012; Worsley et al., 2004). Differences in global measures of CV, CT, and SA between HC, TR, and NTR patient groups were assayed with a one-way ANOVA and followed up with pairwise independent samples *t*-tests (2-tailed).

3. Results

We observed no significant differences in age, IQ, medication dose, illness onset, and illness duration between patient groups ($p < 0.05$) but found a significant difference in IQ in patients compared to HC (Table 1).

3.1 Global measures

A one-way ANOVA was conducted to find the effect of group on CV, CT, and SA. A significant decrease was observed when comparing HC, TR, and NTR groups in a linear trend indicating $HC > NTR > TR$, on global mean CV ($F(2,62) = 6.22, p = .003$), CT ($F(2,62) = 3.38, p = .04$), and near significant in SA measures ($F(2,62) = 3.03, p = .056$) (Figure 1). These differences could not be explained by group differences in total intracranial volume (ICV) ($F(2,62) = 1.47, p = .237$) (Figure 1). A post hoc comparison revealed:

- i) Significant CV reductions ($p = .005$, Bonferroni corrected) in TR ($M = 4.89 \times 10^5$, $SD = 4.78 \times 10^4$) and NTR patients ($M = 5.01 \times 10^5$, $SD = 7.45 \times 10^4$) compared to HC ($M = 5.54 \times 10^5$, $SD = 4.76 \times 10^4$) (Figure 1)
- ii) Significant reduction in mean CT ($p = .046$, Bonferroni corrected) in TR patients ($M = 2.79$, $SD = .22$) and but not NTR patients ($M = 2.83$, $SD = .26$) compared to HC ($M = 2.93$, $SD = .08$) (Figure 1).
- iii) No significant decrease in mean SA in NTR ($M = 9.87 \times 10^4$, $SD = 1.03 \times 10^4$) or TR patients ($M = 9.72 \times 10^4$, $SD = 7.21 \times 10^3$) compared to HC ($M = 1.04 \times 10^5$, $SD = 9.24 \times 10^3$) (Figure 1).

3.2 Differences in cortical volume, cortical thickness and cortical surface area associated with schizophrenia

Vertex-wise analyses showed significant decreases in CV in the patient group compared to HC in seven clusters centred on the right insula ($t = -4.07, p < .001$), left insula ($t = -3.31, p < .001$), left inferior temporal ($t = -5.51, p < .001$) right lateral occipital ($t = -4.54, p < .001$), left precuneus ($t = -4.00, p < .001$), right middle temporal gyrus ($t = -3.16, p < .05$) and right precuneus ($t = -4.04, p < .05$) (Table 2). We observed decreases in CT in patients with schizophrenia compared to HC in two clusters centred on the right superior temporal gyrus (STG) ($t = -3.48, p < .001$) and left inferior temporal gyrus ($t = -3.61, p < .05$) (Table 2). There were significant decreases in SA in patients compared to HC in five clusters centred on the left precuneus ($t = -4.00, p < .001$), right precentral gyrus ($t = -3.33, p < .001$), left inferior temporal gyrus ($t = -5.01, p < .05$), right STG ($t = -3.84, p < .05$), and right medial orbital frontal cortex ($t = -3.59, p < .05$) (Table 2, Figure 2).

Mean cluster values across groups are visualised in Figure 3. Although there were no significant correlations between PANSS symptom scores and significant cortical clusters there was a group trend indicating that PANSS negative scores were related to significant cortical clusters in NTR patients (see Supplemental Materials for details).

3.3 Differences in cortical volume, cortical thickness and cortical surface area associated with treatment resistance

Significant decreases in CV were found in TR patients compared to NTR patients in one cluster incorporating the right frontal and precentral regions ($t = -4.43$, $p < .05$). Similarly, significant decreases in CT were also found in TR patients compared to NTR patients in four clusters including the right parietal and occipital regions ($t = -2.92$, $p < .001$), left temporal regions ($t = -3.65$, $p < .05$), right isthmus cingulate regions ($t = -4.11$, $p < .05$), and left isthmus cingulate regions ($t = -3.65$, $p < .05$) (Table 3). In contrast, an increase in SA in TR patients compared to NTR patients was observed in one cluster incorporating the right postcentral gyrus and superior parietal cortex ($t = 3.47$, $p < .05$) (Table 3, Figure 3). There were no significant correlations between significant cortical clusters and PANSS scores in the TR patient group. However, a group trend showing a negative correlation between negative symptoms and cortical measures in the NTR patient group was observed (see Supplemental Materials).

4. Discussion

In this study we examined differences in measures of cortical morphology between two groups of patients with TR and NTR schizophrenia, and HC. In order to demonstrate differences in cortical measures specific to schizophrenia we compared the entire patient group with HC on all cortical measures and found significant reductions in measures of CV, CT, and SA in patients with schizophrenia compared to HC. Examination of independent patient groups (TR vs NTR) revealed that individuals with TR schizophrenia were found to have more severe reductions in CV and CT across areas of the temporal and frontal lobes, in line with previous reports in this population. However, these results also showed an increase in SA in the superior parietal and postcentral gyrus, contrary to previous research (Kong et al., 2015; Rimol et al., 2012). Taken together it could be proposed that CT reductions may play a significant role in CV reductions in schizophrenia. While further research with a larger sample size is required, these preliminary results could indicate the existence of a neurobiological mechanism specific to CT that is influencing treatment response.

We also observed significant CV and CT reductions in TR compared to NTR patients in regions previously reported as atypical in schizophrenia, including the inferior parietal, lateral occipital cortex, superior temporal sulcus, and lingual and superior temporal gyrus (Nesvåg et al., 2008; Rimol et al., 2010; Szeszko et al., 2012). CV reductions in patients with schizophrenia are one of the most common findings in the condition, beginning with global grey matter reductions characterized by an increase in ventricular volume (Harvey et al., 1993; Honea et al., 2005; Kong et al., 2015; Shergill et al., 2001). The few studies that have compared TR and NTR patients with schizophrenia have found specific CV decreases in the dorso-lateral prefrontal cortex, temporal regions (Rimol et al., 2012), putamen and caudate nucleus (Molina et al., 2010).

In addition to CV, the current study examined CT and SA measures in TR schizophrenia as earlier work has highlighted each of these component measures to represent unique aspects of cortical architecture (Rakic, 1995) with different aetiologies, genetic determinants (Nesvåg et al., 2008; Panizzon et al., 2009) and neurodevelopmental trajectories (Ecker et al., 2014; Hyde et al., 2010). Brain regions found to have decreased CT among schizophrenia patients in this study have been previously indicated across several stages of the disease/condition including; ultra-high risk, first episode psychosis, and chronic schizophrenia (Narr et al., 2005; Plitman et al., 2016; Xiao et al., 2015). Therefore, it has been suggested that reduced CT could be a potential risk factor for schizophrenia and thus may have potential to act as marker of TR (Hedman et al., 2016; Narr et al., 2005; Plitman et al., 2016; Xiao et al., 2015).

There also appeared to be a distinction in regions of CT reductions in TR patients. In agreement with previous literature, this study found significant CT reductions in TR patients in the temporal cortex of the left hemisphere (Cui et al., 2018; Rimol et al., 2010). This lateralisation of reductions in temporal CT may be an important part of treatment response and symptomatology as it is estimated up to 95% of language process occurs laterally in the left hemisphere (Barrick et al., 2005; Geschwind and Levitsky, 1968). Previous research has suggested that the left hemisphere has a dominant role in language processing in HC and it has been suggested that this lateralisation may be dysfunctional or disrupted in schizophrenia (Barrick et al., 2005; Geschwind and Levitsky, 1968). This disruption has been suggested to contribute to auditory hallucinations and language conceptual disorganisation symptoms in patients with schizophrenia (Shenton et al., 1992). The superior temporal sulcus and middle temporal gyrus in particular have been consistently found to be associated with auditory hallucinations in both structural and functional imaging studies (Cui et al., 2018; Shergill et al., 2004, 2003, 2001).

In contrast to previous literature, which has reported no differences or reductions in SA (Szeszko et al., 2012), our data showed an increase in SA in the right postcentral and superior parietal gyrus in TR patients. The parietal lobe has been suggested to be crucial to social cognition, agency and biological motion (Frith et al., 2000; Iacoboni and Dapretto, 2006; Kato et al., 2011). Over-activation of the parietal cortex has been associated with delusions of control, where patients are unable to recognise internal and external biological motion (Kato et al., 2011). Guo and colleagues (Guo et al., 2014) found that a consistent disruption of the medial and mirror neuron system was associated with sensory and cognitive functions, particularly self-processing and agency, over varied illness duration. One could speculate the increase in SA in the superior parietal gyrus in the TR patient group could reflect an over-activation in this region, although this should be interpreted with caution due to the correlational nature and the relatively small sample size in this study.

Previous studies of cortical measures in patients with schizophrenia have included patients treated with clozapine and reported prefrontal cortical atrophy in individuals with a poor response to this treatment (Chiappelli et al., 2017). This study investigated the TR schizophrenia population while controlling for potential confounding effects by excluding patients with schizophrenia who were on or had been on clozapine. This exclusion criterion allowed for the homogeneity of the patient sample to be maintained while still meeting the criteria for TR. However, while CV and CT reduction was observed at this late stage of illness, due to the chronicity of the illness these results could be confounded by several factors. While this study found no significant differences across patient groups in age, illness duration, illness onset, medication dose and intra-cranial volume (ICV), cumulative medication over the lifespan may be a significant factor affecting CV and CT which assumedly would be higher in TR compared to NTR patients (Harrison et al., 2003). Indeed, while medication type and dose were accounted for in this study, medication adherence and its influence on the treatment

response of both groups remains unqualified. In addition, this study mainly included males with schizophrenia and cortical surface measures may differ in the female population. The genesis of these cortical decreases can only be speculated from this patient population as data was collected at a singular time point and thus future longitudinal studies should be required to follow up participants at a number of time points and begin participation in the study when patients are medication-free. In addition this chronic population could have been exposed to earlier comorbidities such as depression or mood disorders and secondary illnesses such as substance abuse and prolonged stress, which may have impacted the underlying brain pathology (Heinrichs et al., 2017; Konopaske et al., 2007). Recent studies have suggested that stress could contribute to an increased rate of cortical thinning, which should be considered when discussing patients with chronic schizophrenia (Harrison, 1999; Konopaske et al., 2007). While these various factors make it difficult to fully characterize cortical differences between TR and NTR patients, there is no reason to conclude that these factors would differentially impact TR versus NTR patients.

In summary, this study demonstrated that TR patients with schizophrenia show specific and significant reductions in CT and CV and increases in SA compared to NTR patients. These cortical differences were located in regions of particular interest to schizophrenia in the temporal, parietal and medial regions (Rimol et al., 2012; Shergill et al., 2001). Since CT reductions have been reported at all stages of schizophrenia, further research should be conducted to determine the nature of the relationship between CT, schizophrenia illness onset and trajectory. While the causal impact of these cortical changes remains elusive, it can be speculated that a deficit in CT may make an organism more intolerant to insult and therefore predispose the organism to neurological insult or illness outbreak. These cortical measures may reflect mechanisms underlying aspects of neurological disorganisation and pathology in many

respects. Future studies require longitudinal scans at several time points to determine reliable pathological trajectories, and larger sample sizes are needed to confidently show generalizable effects.

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Conflict of interest

None

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Tables

Table 1. Demographics and clinical data including the Weschler abbreviated scale of intelligence (WASI), National Statistic for Socio-economic Classification (NS-SEC), Chlorpromazine equivalent (CPZ) and Positive and Negative Symptom Scale (PANSS) expressed in means (M) and standard deviations (SD).

	HC (N=23)		NTR (N=21)		TR (N=21)		Group statistics	
	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>	$\chi^2(2)$	<i>P</i>
Female(Male) (%)	26(74)		14(86)		14(86)		1.18	.555
							<i>F(2,62)</i>	<i>P</i>
Age	38.4	10.0	41.3	10.4	41.5	10.6	0.46	.641
WASI IQ	115.8	11.7	91.86	14.8	97.1	16.4	16.8	<.001
NS-SEC	3.13	1.62	3.74	1.88	3.39	1.76	0.65	.525
							<i>t(42)</i>	<i>P</i>
Onset age (years)			27.7	6.2	26.0	7.7	-0.75	.431
Illness duration (years)			14.1	10.1	15.5	8.8	0.46	.650
CPZ equivalents (mg)			280.3	147.1	383.5	236.5	1.88	.067
PANSS score								
Positive			10.7	2.1	20.5	3.1	12.10	<.001
Negative			13.1	4.6	19.5	4.6	4.08	<.001
General			23.6	5.1	34.9	9.2	4.91	<.001
Total score			46.9	10.3	76.2	10.6	9.14	<.001

Table 2. Clusters of significance (RFT, $p < .05$) between treatment resistant (Treatment Resistant) and non-treatment resistant (NTreatment Resistant) patients with schizophrenia. Brodmann Area (BA), left(L), right(R), 'Vertices' indicates the number of vertices within the cluster, tmax represents the maximum t statistic within the cluster at the x y z Talairach coordinates reported, pcluster is the cluster corrected P value for significance reporting.

Measure	Cluster	Region Labels	Hemisphere	BA (tmax)	Vertices	Talairach			tmax	pcluster
Cortical Thickness TR>NTR	1	inferior parietal cortex, lateral occipital cortex, middle temporal gyrus	R	39	4462	46	-56	31	-2.92	6.11×10^{-3}
	2	isthmus-cingulate cortex, precuneus cortex	R	30	2774	23	-58	13	-4.11	2.67×10^{-2}
	3	banks superior temporal sulcus, middle temporal gyrus, superior temporal gyrus	L	22	2956	-62	-18	0	-3.65	2.99×10^{-2}
	4	isthmus-cingulate cortex, lingual gyrus, precuneus cortex	L	19	2663	-20	-48	-1	-3.65	3.91×10^{-2}
Cortical Volume TR>NTR	1	caudal middle frontal gyrus, precentral gyrus	R	6	2773	42	-2	29	-4.43	4.10×10^{-2}
Cortical Surface Area TR>NTR	1	postcentral gyrus, superior parietal cortex	R	40	2726	31	-41	55	3.47	1.75×10^{-2}

Table 3. Clusters of significant reduction (RFT, $p < .05$) between patients and HC on cortical surface measures. Brodmann Area (BA), left(L), right(R), 'Vertices' indicates the number of vertices within the cluster, tmax represents the maximum t statistic within the cluster at the x y z Talairach coordinates reported, pcluster is the cluster corrected P value for significance reporting.

Measure	Cluster	Region Labels	H	BA	Vertices	Talairach			tmax	Pcluster
						X	Y	Z		
Cortical Thickness Patients>HC	1	Insula, precentral gyrus, superior temporal gyrus, supramarginal gyrus , transverse temporal cortex	R	13	4764	33	7	12	-3.48	1.21x10 ⁻³
	2	fusiform gyrus, inferior temporal gyrus, middle temporal gyrus	L	20	2586	-31	-38	-16	-3.61	1.05x10 ⁻²
Cortical Volume Patients>HC	1	Insula, lateral orbital frontal cortex, pars opercularis, postcentral gyrus, precentral gyrus, superior temporal gyrus, supramarginal gyrus , transverse temporal cortex	R	44	14537	48	5	13	-4.07	7.95x10 ⁻⁶
	2	Insula, lateral orbital frontal cortex, medial orbital frontal cortex, pars opercularis, precentral gyrus, superior temporal gyrus	L	11	6797	-6	44	-20	-3.31	1.93x10 ⁻⁵
	3	inferior temporal gyrus, middle temporal gyrus	L	20	3423	-53	-22	-25	-5.51	5.74x10 ⁻⁴
	4	entorhinal cortex, fusiform gyrus, lateral occipital cortex, parahippocampal gyrus	R	17	3789	21	-89	-2	-4.54	5.73x10 ⁻⁴
	5	isthmus-cingulate cortex, precuneus cortex	L	30	4093	-5	-46	22	-4.00	1.67x10 ⁻³
	6	inferior temporal gyrus, middle temporal gyrus	R	20	2270	53	-27	-16	-3.16	2.06x10 ⁻²
	7	isthmus-cingulate cortex, precuneus cortex	R	23	2500	5	-46	22	-4.04	4.21x10 ⁻²
Cortical Surface Area Patients>HC	1	isthmus-cingulate cortex, precuneus cortex	L	30	4207	-6	-47	20	-4.00	3.83x10 ⁻⁴
	2	pars opercularis, postcentral gyrus, precentral gyrus	R	9	3646	49	4	21	-3.33	2.24x10 ⁻³

3	inferior temporal gyrus, middle temporal gyrus	L	20	1806	-53	-23	-25	-5.08	6.50×10^{-3}
4	Superior temporal gyrus, transverse temporal cortex	R	22	2255	55	-7	-2	-3.84	9.92×10^{-3}
5	medial orbital frontal cortex, superior frontal cortex	R	11	1541	10	50	-20	-3.59	2.84×10^{-2}

Figure legends

Figure 1. Trends in mean global measures across groups. Measures include estimated intracranial volume (ICV), mean cortical volume (CV), mean cortical thickness (CT), and mean pial surface area (SA) across groups including healthy controls (HC), treatment responsive (NTR), and treatment resistant (TR) patients with schizophrenia.

Figure 2. Reduced cortical measure clusters for Treatment Resistant compared to Non-Treatment Resistant. Regions of significantly reduced (RFT, $p < .05$) cortical thickness, cortical volume, and cortical surface area in individuals with Treatment Resistant schizophrenia compared to Non-Treatment Resistant schizophrenia. See Table 2 for further statistical cluster details.

Figure 3. Reduced cortical measure clusters for patients compared to healthy controls. Regions of significantly reduced (RFT, $p < .05$) cortical thickness, cortical volume, and cortical surface area in individuals with schizophrenia compared to HC. Corrected t-maps see on the left and uncorrected t-maps seen on the right. See Table 3 for further statistical cluster details.